Staff Summary Sheet

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Summary

1. Purpose: To provide security and policy review on the conference paper at Tab 1 prior to release to the public.

2. Background:

- *Author(s)*: Scott Gruber, Chad Hager, Hyukseong Kwon, Rajnikant Sharma, Josiah Yoder, and Daniel Pack

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Tab
1. Copy of article

AF Form 1768, Staff Summary

UAV Handbook – Payload Design of Autonomous Small UAVs

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Abstract

In this section, we present a payload design process for small unmanned aerial vehicles (UAVs). We detail several payload design principles to overcome various constraints imposed by the stringent weight, power, and space requirements of small UAVs. Throughout the section, we demonstrate the efficacy of these principles with an example payload for a fixed wing small UAV used by the Academy Center for UAS Research at the US Air Force Academy. In this example application, a UAV is to be used to autonomously search, detect, localize, and track a ground target. The system requirements generated by this example application are closely related to those for other small UAV applications.

I. Introduction

As the number of applications grows for small UAVs, it is clear that the UAV community must learn to work effectively within the limited space and weight capacity constraints of such UAVS. These limitations drive several additional challenges such as electronic noise interference (a risk increased by the proximity between electronic components) limited power, and reduced payload (sensor and computation) capability.

Designing a small UAV payload requires balancing the major performance requirements of the mission. For example, an autonomous system will require less user input and communication bandwidth, but will require more onboard components. Additional payload components will increase the aircraft weight and power requirements, reducing overall mission time. With a careful design procedure, the overall weight and power can be reduced; however, this will increase the development costs and reduce the payload flexibility of the final craft.

The examples above illustrate major tradeoffs in the design of a small UAV payload:

- Autonomy versus human interaction
- Autonomy (onboard processing) versus communication bandwidth

- Autonomy (onboard capability) versus flight time
- Minimalist design versus flexibility and adaptability
- Maximum design (optimization) versus simplicity

These system-level decisions will affect each of the UAV subsystems, shown in Figure 1. Decisions made for one subsystem also will affect the design of another subsystem. While managing these tradeoffs, the overall small UAV system-level payload performance requirements must be considered while addressing each sub-system. .

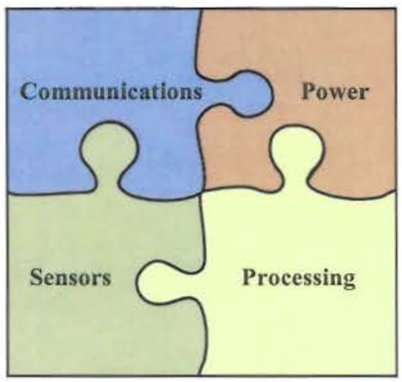

Figure 1. Major Payload Subsystems

Payload Mission Requirements

Before a detailed design can be developed, the payload requirements must be identified and documented. Typical questions that must be answered are:

- What is the mission objective? For example, searching for specific targets, setting up surveillance posts, or providing a communications relay.
- What is the required flight duration?
- How long will payload systems need to be operating on the ground before the flight?
- What maximum distance will the UAV be travelling from the ground station?
- What are the allowed frequencies and bandwidths that can be used for communications?
- What are the situational awareness requirements of the ground station operator?
    - Imagery required? Frames per second? Quality? Size?
    - UAV position/attitude? Mission task status? Payload and UAV health?
- Will other devices be operating in the same area that can cause communication interference?
- What are environmental requirements (Vibration, shock, humidity, temperature)?

In Subsection, II, we develop payload requirements for a small UAV with an illustrative mission in Subsection III. Sample payload weight, power, and space budgets following Subsection IV and an iterative payload design process is illustrated in Subsection V. We conclude the section by addressing other factors that can affect the payload design.

II. Preliminary Payload Design Budgets

The preliminary payload design is governed by the weight and volume available for the payload. Power, in the form of batteries, is a main contributor to the payload's weight. Any reduction in the power requirements of the payload subsystems will result in either an overall weight reduction or an increase in the possible mission time. In the flow diagrams below that describe the design process for each subsystem, WPV represents weight, power, and volume.

When developing a preliminary design budget, an investigation of likely components needs to be completed. These components are then used to determine the preliminary allocations of weight and volume. To start this sizing, a preliminary power budget is useful since the battery is a major contributor to the overall weight.

The Power Budget

For a small UAV gasoline propulsion system, a generator is impractical due to the weight, so a battery is necessary to support the payload system. If the propulsion system is electric, the propulsion batteries typically are used just for propulsion to maximize flight time, again requiring the payload to have its own battery. Note that if the payload has small power requirements, a small UAV design may opt to use the propulsion batteries to support the payload with the understanding that the flight duration will be impacted. This section will focus on a payload system with its own battery.

An estimated payload is used to get an overall sizing of the payload power requirements. Table 1 presents an example payload using a single board computer (SBC) with an Atom-based processor, a 2.4 GHz radio, and a camera as the key payload components. Note that the camera in this example has electronic panning capability so it addresses pointing requirements of an electro-optical (EO) sensor system. Since this table is developed early in the design, a 30% margin is added to the power for future use if needed as the design progresses. Based on this analysis, the SBC system (processor and disk) has a 14 watt budget, the communications system has a 3 watt budget, and the EO sensor system has a 3.6 watt

budget. Note that the estimated requirement for the wireless card assumes it is transmitting a little more than 50% of the time, and that the solid state disk (SSD) has 50% utilization. When the mission's requirements are more fully understood, these average usages can be adjusted. For the example battery and estimated power requirements, the available battery life is 0.9 hours. If the combination of ground time and flight time is more than 0.9 hours, a higher capacity battery should be used in this estimate.

Component	Voltage	Current	Watts
Aurora/Corona SBC	5	2.0	10.0
32GB SSD	5	0.8	4.0
Ubiquiti XR2 Wireless Card	3.3	0.9	3.0
Axis 212 PTZ Camera	5	0.7	3.6
Misc. Parts (servo switch, RC receiver, etc)	5	0.2	1.0
Total Watts			21.6
		Efficiency	**Watts**
Adjusted for efficiency of DC-DC converter		0.9	24.0
Adjusted for 30% margin		0.7	34.3
		Batt Volt	**Needed Current**
Battery voltage & current for required power		14.8	2.3
		Batt AH	**Available hours**
Lithium polymer battery amp hours (AH) & available operational hours		2.1	**0.9**

Table 1. Example Power Budget

The Weight Budget

Payload weight and volume are primary constraints in small aircraft payload design. The maximum weight is usually a firm design constraint, predetermined by the aircraft's lift and gross weight limitations determined by regulations (such as FAA flight rules) on small aircraft design. Using the preliminary components from the power budget, a preliminary weight budget can be generated (Table 2). This example assumes that the small UAV allocation for payload is five pounds. In this case, the margin factor is 20%. The resulting weight budgets are: 27% for the SBC system (includes the SSD), 4.5% for the communications system, 22.5% for the camera, and 26% for the power system, including the miscellaneous components such as brackets, wires, and connectors.

Component	Weight (gms)	Percent of Whole
Aurora/Corona SBC w/ enclosure	400	18.0
32GB SSD, enclosure, and cable	200	9.0
Ubiquiti XR2 Wireless Card, cables, antenna	100	4.5
Axis 212 PTZ Camera	500	22.5
Misc. Parts (servo switch, RC receiver, etc)	100	4.5
Power System (Battery, DC-DC, wires)	480	21.5
Total Weight	1,780	
Adjusted for 20% management factor	2,225	20.0
Total Weight Estimate	2,225	100
UAV Payload Weight Allowance	2,270	
Additional Weight Buffer	45	

Table 2. Example Weight Budget

Space Allocation

When considering the available space for payload components, it is not enough to simply budget the total volume available for components. Instead, components must be placed within the payload compartment(s) so that they are not overlapping, can be mounted, and do not cause electronic interference to each other. Furthermore, components must be arranged so that the aircraft center of gravity is maintained for stable flight.

Figure 2 is an example UAV. To maintain the center of gravity in the appropriate region of the aircraft, the heaviest objects, the propulsion and payload batteries, are placed in the front of the fuselage with final placement to maintain the center of gravity.

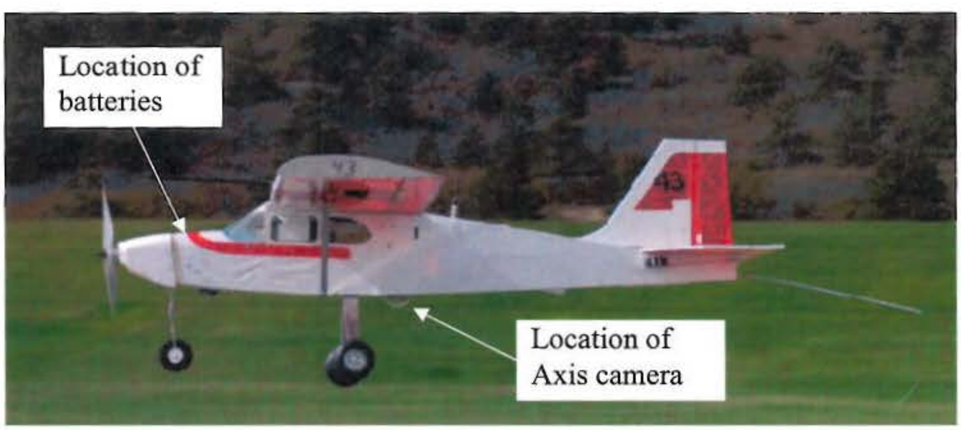

Figure 2. Kadet Senior UAV used in the Center

III. Subsystems Design

A flow chart for each subsystem describes the design process. The number in each flow element corresponds to the items in the accompanying lists that further explain the flow chart elements.

Communications Subsystem

Communication is an integral requirement even for autonomous systems, which still require operator monitoring and control over-ride capabilities. A reliable communication system is required for the onboard components (such as the autopilot and computer) to communicate with a ground station where human operators can monitor all events perceived by the UAV adjust mission tasks or objectives during the mission (see Figure 3).

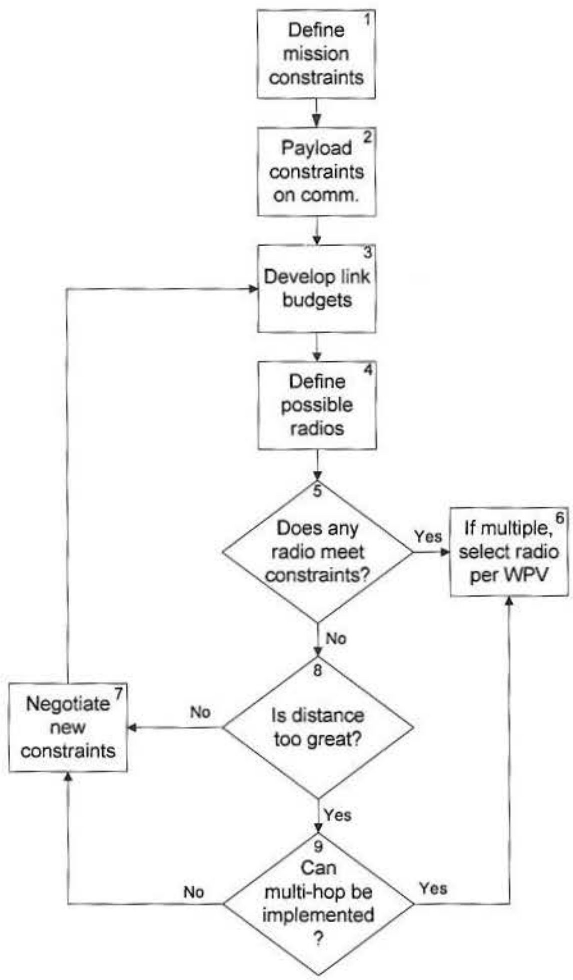

Figure 3. Communications Subsystem Design Flow

1) Define mission constraints.

a. Allowed frequencies. Unless licensed radios are available, a typical small UAV uses the unlicensed ISM (industrial, scientific, and medical) bands. For such UAVs, the 902 – 928 MHz, the 2400 – 2483.5 MHz, and the 5725 – 5850 MHz bands are commonly used. These bands can support one to multiple 20 MHz channel bands and compliant radios are readily available. Transmission power is restricted per FCC regulations so radios and antenna gain need to be selected such that they comply with these regulations. Note that the 902 – 928 MHz band is frequently used for the autopilot wireless link.

b. Maximum distance. This distance will be used in determining your link budget.

c. Number of UAVs in flight will determine if a multi-hop network is possible and the total bandwidth that may be available at the ground station.

d. Other devices operating in the same area will create noise and limit the communication system range if broadcasting over the same frequencies.

e. Situational requirements of ground station operator will drive the bandwidth requirements of the system. A number of key points are:

    i. What command and control messages are necessary and what is the frequency of the messages?

    ii. What aircraft status messages such as position, aircraft health, stage in mission, etc. need to be reported?

2) What size and compression of images are acceptable? Besides the WPV constraints, what other requirements on the communications system are generated by the other components of the payload?

    a. What are the weight and power allocations for the communications system antenna?

    b. What are the available input/output (I/O) interfaces for the on-board computer?

3) Develop a communications link budget. A communications link budget is a method to estimate how well a communications channel will work for a specific system. It is a good tool for comparing multiple radios, antennas, and frequency bands. This section will not provide a detailed description but gives an example of how this tool can be used.

    The link budget is based upon an expanded Friis equation, which is linear when represented in decibels: $P_{R_{dB}} = P_{T_{dB}} + G_{T_{dB}} + G_{R_{dB}} - L_{FS_{dB}} - L_{Cbl_{dB}} - L_{Pol_{dB}} - L_{Pnt_{dB}}$, where transmit and receive gains are the maximum gains of the antennas (G_T, G_R), *free space loss* (L_{FS}) is attenuation due to spreading of energy with distance, and cabling losses (L_{Cbl}) are due to the interconnects between the radio and the antenna. The actual gain of an antenna varies as measured in space around the

antenna. The typical antennas used on a UAV are dipoles and monopoles which have a gain pattern similar to a doughnut, with the antenna being the axle of the doughnut. These antennas are referred to as omni-directional due to a similar gain in all directions away from the antenna.

The shape of an antenna generates an alignment of its electric field, referred to as polarization. The most common type used in UAVs is linear polarization, where the electric field aligns with one plane, in the case of a dipole, aligned with the length of the antenna. Even if the antennas have no polarization loss (L_{Pol}), there will still be additional pointing losses (L_{Pnt}) because the aircraft is at a different altitude from the ground station and may be rolling away from or toward the ground station resulting in antenna pointing losses.

Two radio systems are being compared in Tables 3 and 4, a 2.4 GHz radio and a 900 MHz radio. A data bandwidth of 11Mb/s needs to be maintained, resulting in the required transmit and receive powers presented in Table 3 from the radio specifications. Other system parameters are also defined in Table 4.

Parameter	**2.4 GHz radio**	**900 MHz radio**
Required receive power for 11 Mb/s	-92 dBm	-90 dBm
Transmit power for 11 Mb/s	28 dBm	28 dBm
Maximum distance	1 mile	1 mile
Ground Station Antenna Gain	4 dBi	4 dBi
Aircraft Antenna Gain	2 dBi	0 dBi
Maximum point error	half power beamwidth	half power beamwidth
Maximum bank angle	15°	15°
Radio to antenna cable losses at each end	0.5 dB	0.5 dB

Table 3. Communications Link Budget Requirements

Parameter	**2.4 GHz radio**		**900 MHz radio**	
Power Transmit for 11 Mb/s	28.0	dBm	28.0	dBm
Ground Cabling Loss	-0.5	dB	-0.5	dB
Ground Station Antenna Gain	4.0	dBi	4.0	dBi
Ground Pointing Loss (half power pointing error)	-3.0	dB	-3.0	dB
Free Space Loss	-104.4	dB	-95.8	dB
Polarization Loss	-0.3	dB	-0.3	dB
Aircraft Pointing Loss (half power pointing error)	-3.0	dB	-3.0	dB
Aircraft Antenna Gain	2.0	dBi	0.0	dBi
Aircraft Cabling Loss	-0.5	dB	-0.5	dB
Power Received (total of above)	-77.7	dBm	-71.1	dBm
Required receive power for 11Mb/s	-92.0	dBm	-90.0	dBm
Link Margin	14.3	dB	18.9	dB

Table 4. Communications Link Budget Example Solution

Table 4 presents the solution of the link budget. The free spaces losses are calculated as:

2.4 GHz radio: 2.45 GHz: $20 \log_{10}((4\pi\ 1609)/0.122) = 104.4$dB
900 MHz radio: 915 MHz: $20 \log_{10}((4\pi\ 1609)/0.328) = 95.8$dB

And the polarization loss is calculated from the maximum bank angle as:

Polarization Loss: $20 \log_{10}(\cos(15°)) = 0.3$ dB

A good link margin should be above 10 dB. In this case, both radios exceed the link margin. Since both systems have sufficient link margin, other factors should be considered such as in-band interferers. If the autopilot wireless link uses the 900 MHz band, it will be generating noise for that radio. It would then be better to choose one of the 2.4 GHz channels.

4) Define possible radios. The link budget in Step 3 guides the choices of possible radio solutions. After possible radios are chosen, additional link budget comparisons can be made for final selections. Other considerations when choosing radios are:
    a. What I/O interfaces are available from the computer? What antenna connectors are available on the radios?
    b. Which antenna will cover your mission area well?
    c. What are the costs and delivery times?

5) Select radios that meet the communication system constraints.

6) Introduce WPV factors to make your final decision. Reduction in weight and power can either leave more allowance for other payload subsystems, or increase flight time.

7) If a solution cannot be found, identify what bandwidth can be supported and develop new constraints. Multiple design loops are typically required to develop a robust system.

Autopilot

An autopilot is the autonomous low-level flight control system responsible for maintaining the stability of a UAV and guiding it to waypoints. Most commercially available autopilots include GPS, an inertial measurement unit (IMU), and a pitot tube for estimating altitude and airspeed. When selecting an autopilot, the trade-offs are primarily between WPV, cost, and performance.

Single Board Computer Subsystem

For a UAV to be truly autonomous, the UAV needs an onboard computer. Autonomy is not required for many small UAV applications today, but we will witness more and more cases that will require autonomous control and sensing decisions to be made onboard UAVs (see Figure 4).

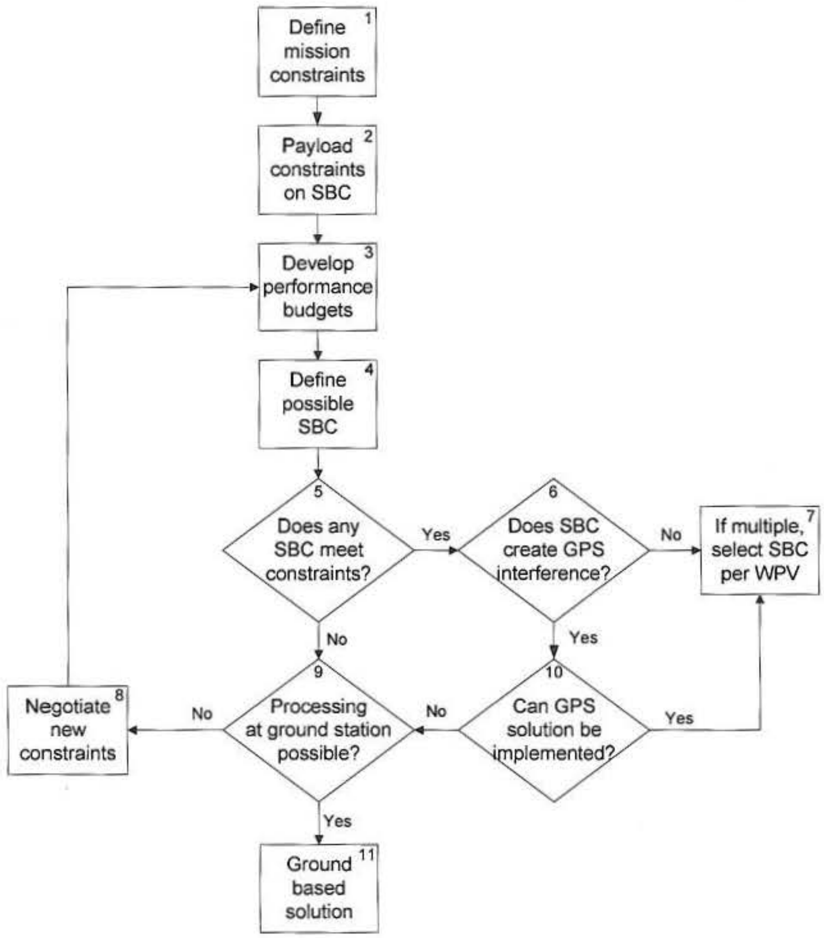

Figure 4. SBC Subsystem Design Flow

Note that references to the SBC refer to the entire computing system, including storage devices.

1) Define mission constraints such as mission time and environmental requirements.

2) Define other payload subsystem requirements imposed on the SBC system.
    a. What are the computing and I/O requirements?
    b. What is the weight and power allocation for the SBC system?

3) Develop performance budgets. Table 5 is an example that assigns the SBC resources to different software tasks.

Priority	Component	CPU Allocation
1	Image capture	10%
2	Planning and Control	10%
3	Image Processing	45%
4	Data Fusion	15%
5	Housekeeping	10%
	Total	100%

Table 5. Example of Aircraft Software Budget Table

4) Look for possible SBC solutions that meet the performance budgets.

5) Were any SBCs found that meet the requirements?

6) If there were, does the SBC create any GPS noise?

7) If multiple choices exist, select the best choice using WPV factors. Reduction in weight and power can either leave more allowance for other payload subsystems, or increase flight time.

8) If no viable computing solution can be found, new constraints must be defined.

9) If an on-board SBC solution can't be found, is doing processing on the ground a viable solution?

10) Can a solution to the GPS noise issue be found?

11) Areas to consider for a ground-based computing solution:
    a. A faster computer that doesn't need to meet weight requirements could be available for ground use.
    b. With all processing on the ground, what happens to the success of the mission if messages are lost?

EO Sensor Subsystem

Though other sensors may be used, the electro-optical sensor (i.e. a visible-spectrum camera) is predominantly employed in small UAVs. This section discusses design considerations for the EO sensor

but the methods can be readily applied to other types of sensors. The EO sensor subsystem includes the sensor, capture method, and any requirement for panning the sensor (see Figure 5).

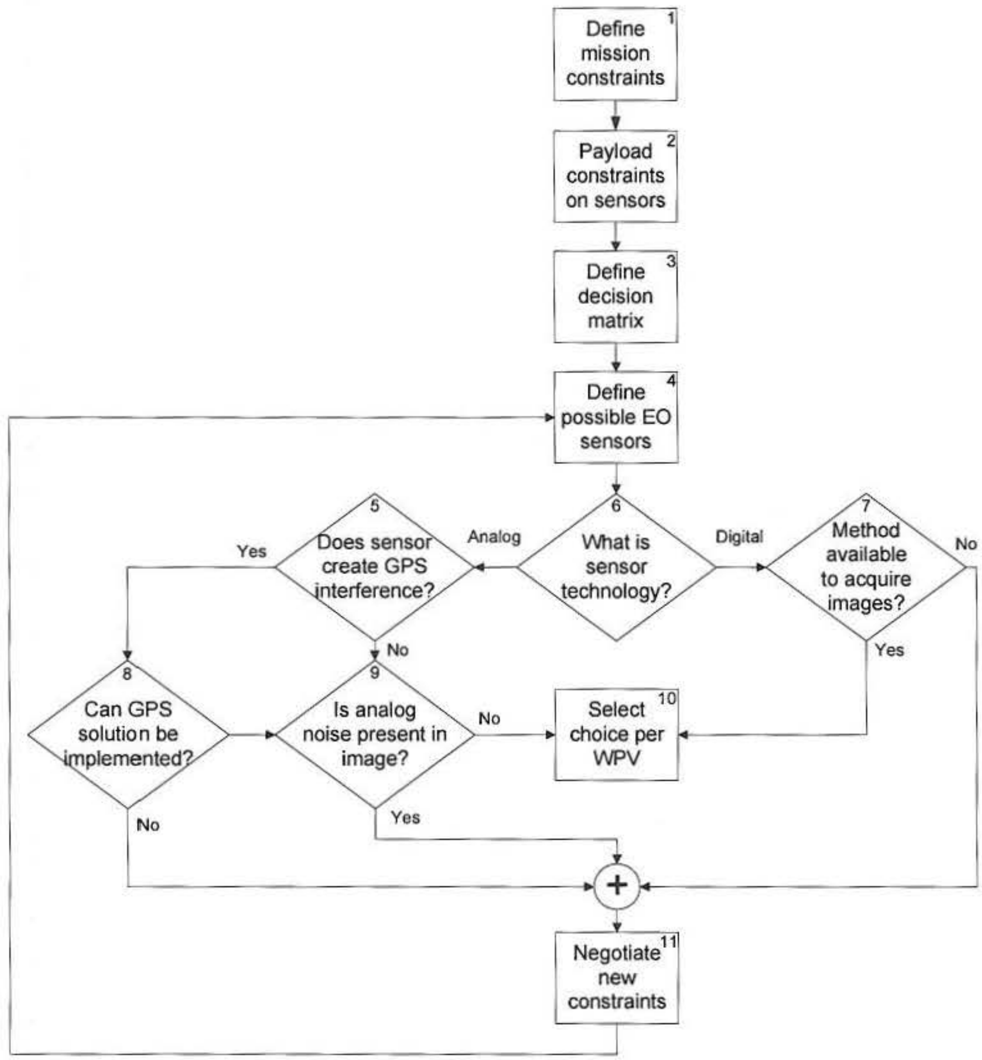

Figure 5. EO Sensor Subsystem Design Flow

1) Define mission constraints.

2) Determine EO sensor system constraints.

3) Develop a decision matrix for the EO sensor. Table 6 presents an example matrix used by the Center to evaluate three possible candidates. The Axis camera was chosen for our application.

	AXIS-212 PTZ	WV-SC385 [12]	EVI-D100 [13]
Manufacturer	Axis Communications	Panasonic	Sony
Image sensor type	1/2" CMOS	1/3" CMOS	1/4" Super HAD CCD
Pixel resolution	640 x 480	1280 x 960	768 x 494
Frame rate	30 fps	30 fps	30 fps
Video signal output	HTTP / FTP (digital) MPEG-4 JPEG	HTTP / FTP (digital) H.264 JPEG	NTSC (analog) Y/C
Pan / tilt	+/- 70° / +/- 52° (electronic)	0-350° / -30 – 90° (mechanical)	+/- 100° / +/- 25° (mechanical)
Zoom	3x electronic zoom	18x optic + 12x digital zoom (3.2 – 55.2° (H) / 2.4 – 42.1° (V) AOV)	10x optic + 40x digital zoom (6 – 65° AOV)
Weight	504 grams	900 grams	860 grams
Dimension	89 x 94 x 77 (mm^3)	115 x 115 x 155 (mm^3)	113 x 130 x 122 (mm^3)
Power consumption	3.6 W	12.0 W	13.2 W

Table 6. Comparison of Pan-Tilt-Zoom Camera Systems

4) Identify possible EO sensors. Two general types of EO sensors are typically employed: analog and digital. The analog sensor uses either the National Television System Committee (NTSC) format or the Phase Alternation Line (PAL) format. An analog sensor requires an image capture board to convert the image stream into individual images in a common format such as Joint Photographic Experts Group (jpeg) that can be digitally processed. Digital sensors provide an image that can be processed directly, usually in a raw format.

5) Will the analog sensor generate GPS noise? Though the EO sensor radio frequency noise generation should be measured, NTSC analog sensors use a clock speed that has a harmonic at the GPS frequencies that causes significant degradation to GPS performance. This noise is further increased during the image capture process. PAL EO sensors use a different frequency and do not generate the same noise.

6) Determines path between analog and digital.

7) Many digital EO sensors do not directly connect to a common SBC bus such as USB or Ethernet, thus an FPGA interface must be used. Test interface units are typically available from the manufacturer of the EO sensor though they tend to be bulky and don't have robust connections. Some complete sensors are available with either Ethernet or USB interfaces.

8) GPS noise may be mitigated using a PAL-based sensor. If a UAV is large enough, physically separating the analog sensor and capture board from the GPS antenna may sufficiently mitigate the GPS noise issue.

9) Most analog sensors interlace their image which means that it creates all odd lines in an image and then the even lines in an image. This can create jagged edges since the UAV is moving while the odd lines are captured followed by the capture of the even lines. Edge detection algorithms are adversely impacted by the jagged edges.

Other considerations:

- If an analog sensor is used and images are transmitted to the ground station for processing, additional noise will be introduced from the analog wireless transmission.
- If a greater pan angle is required just for orbiting an object, mounting the sensor at an angle and then orbiting always in the direction that favours the tilt of the camera may eliminate the need for electronic panning or a more cumbersome gimbal system.

Power Subsystem

The power system includes batteries and DC-DC converters. Figure 6 shows the design flow.

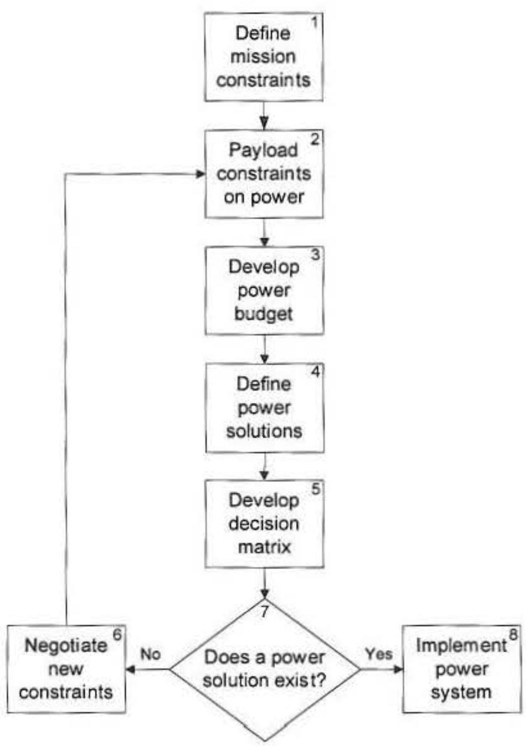

Figure 6. Power Subsystem Design Flow

1) Define mission constraints.

2) Identify payload requirements on the power system.

3) After the initial estimates, as equipment choices are made the power budget should be periodically updated using the technique displayed in Table 1.

4) Nickel metal hydride (NiMH) and lithium polymer (li-po) batteries are the most common battery technologies in use for small UAVs. Table 7 presents a comparison of the two types for comparable capacity batteries. Though li-po is more expensive, it is a better choice for UAVs because of the higher power density for the same weight. Special care must be taken with li-po technology to ensure that no overcharging occurs and that the batteries are not discharged to less than three volts per cell.

Criteria	**Nickel Metal Hydride**	**Lithium-Polymer**
Cost	Half of Lithium Polymer	$420
Rechargeable	Yes	Yes
Volume (cu. in.)/AH	13.6	6.6
Weight (ounces)/AH	18.1	6.9
Charge Rate (Amps)	1	8

Table7. Battery Trade Analysis

DC-DC conversion is done with a switching power supply. DC-DC supplies in the **Advanced Technology eXtended** (ATX) FORM FACTOR that have been developed for use in automobiles is a good choice. These supplies can use a wide input voltage range and output 3.3, 5, and 12 DC voltages that are commonly used by SBCs, sensors, and communication systems.

5) A decision matrix allows the various objectives of a power system to be compared numerically.

6) If no viable power solution can be found, new constraints must be defined.

7) Decision box regarding existence of viable power solution.

8) Implement the selected power system, always striving for reduced weight and size wherever possible.

IV. Conclusions

In this chapter, we discussed payload design principles for small UAVs. Our payload design example was based on a design for an autonomous target detection and tracking mission performed by UAVs used in the Academy Center for UAS Research at the US Air Force Academy. We discussed the subsystems required for related UAV missions and the constraints such as power, weight, and electronic interference.

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